



Reconciling irrigation demands for agricultural expansion with environmental sustainability - A preliminary assessment for the Ica Valley, Peru

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ABSTRACT

Irrigation expansion driven by a growing global food demand is threatening the sustainability of scarce water resources. An exemplar is the Ica Valley in Peru which has experienced significant agricultural transformation over the last three decades with uncontrolled abstractions leading to over-exploitation of the Ica-Villacuri aquifer. This paper critically assesses the impacts of agricultural expansion on the long-term sustainability of groundwater resources in the Ica Valley. We apply a combination of spatial analysis and irrigation modelling by farming type (large and small-scale), followed by a multi-criteria assessment on irrigation water use. Historical trends in cropped area were analysed using Landsat satellite imagery to identify agricultural expansion and the changing composition between large and small-scale farms. The blue water footprint (WF_{blue}) for croplands was calculated distinguishing between surface and groundwater abstractions for eight disaggregated geographical zones within the Ica Valley. The economic benefits of water consumption were assessed using the water productivity indicator, and the environmental sustainability of water resources spatially evaluated using a monthly blue water sustainability index and adapted version of the groundwater debt. The analyses showed that the groundwater footprint accounts for 87% of the total WF_{blue} (483 Mm^3) with 286 Mm^3 groundwater consumed under unsustainable conditions (exceeding groundwater recharge). The highest water productivity ($2.4\text{--}5.4 \text{ sol/ton}$) occurs in zones with intensive groundwater abstractions and where most large-farms are located, but it is also where the sustainability issue is most acute. Modelling showed that based on existing climate conditions and cropping patterns, irrigated agriculture is locally unsustainable throughout the valley, with the exception of small-scale farming in the peri-urban and middle valley areas. Around 10% of total aquifer recharge results from small-scale irrigated farming, whereas recharge from large scale farming is negligible. The greatest impacts occur in zones dominated by large-scale farms, where a period of 3.7–5.9 years is estimated to be needed to replenish water resources consumed by agricultural production. There is thus an urgent need to manage water resources more effectively and promote more sustainable use of water to protect both traditional and agro-export agricultural practices as well as allocations for urban water supply and the environment.

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1. Introduction

The sustainability of irrigation in the context of supporting increases in global food production is under intense scrutiny because

of its major impact on the depletion of freshwater resources (Jägermeyr et al., 2017). Currently about half the volume of irrigation water used globally is considered unsustainable and at the expense of environmental flows and groundwater stocks (Rosa et al., 2019) with about 20% of irrigation dependent on non-renewable groundwater abstractions (Wada et al., 2012). Globally, nearly half (40%) the irrigated area relies on groundwater (FAO, 2017) and their over-exploitation is one of the main global water-

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related challenges (Castilla-Rho et al., 2019; Gleeson et al., 2012). International food trade has been identified as the main driver for rising levels of irrigation demand, leading to rapid rates of depletion in both groundwater (Famiglietti, 2014; Wada et al., 2014) and surface water resources in many regions (Vörösmarty et al., 2010). It is estimated that 15% of unsustainable water consumption is 'embedded' in international food trade (Rosa et al., 2019), with groundwater representing 11% of depleted resources virtually embedded in food exports (Dalín et al., 2017).

Peru is an upper middle-income country which has reported an average annual growth rate of 5.6% in gross domestic product between 2002 and 2016 (The World Bank, 2019). Peru also had a 150% increase in economic returns linked to export activity since 2007 (WITS, 2017). In the early 1990s, the main agro-export commodities were coffee, sugar and cotton. The latter two have gradually been replaced by high-value horticultural crops including asparagus, onions, and fruits such as grapes and mangoes (Torres-Zorrilla, 2019). In 2017 Peru became the second largest exporter of asparagus in the world (Moore, 2017) and the third largest exporter of grapes (Andina, 2017). In the Ica Valley, south of Lima, groundwater is abstracted from the Ica-Villacuri aquifer; the largest aquifer in Peru which represents about 40% of the country's groundwater resources (Oré, 2005). The region has undergone significant agricultural transformation and growth, with production contributing to approximately one-third of the country's total horticultural and fruit exports (Oré, 2005). However, whilst having positive impacts on both the economy and employment, agricultural expansion in the Ica Valley has also led to detrimental effects on water resources, principally groundwater (Muñoz, 2016; Schwarz and Mathijs, 2017; Williams and Murray, 2018) with the water table reported to be declining by 4 m annually in the north-west of the valley (Zegarra, 2018). This has taken place despite a ban on drilling of new wells since 2008 (Oré and Muñoz, 2018). Agricultural activity, coupled with a growing population have increased overall water demand (Damonte and Boelens, 2019), while the natural variability in precipitation and a changing climate have reduced available water supplies (Andres et al., 2014). In 2010, this resulted in the declaration of a water emergency situation in the region (Gobierno Regional de Ica, 2010).

Over the last decade, the Peruvian National Water Authority has encouraged sustainable agricultural production by using the water footprint (WF) concept with two alternate methodological frameworks, (i) the volumetric Water Footprint Framework method (Hoekstra et al., 2011) and (ii) the ISO 14046 life-cycle based assessment (ISO, 2014) (ANA, 2020). The volumetric WF represents the amount of water consumed by a nation or a specific geographical location, by sector, product or company (Water Footprint Network, 2019). The consumptive part of the WF for crops includes the blue WF (i.e., surface and groundwater evapotranspired) and green WF (i.e., water from precipitation that is stored in the root zone and evapotranspired). In Peru WF studies have been undertaken at the national and regional levels for the main crops grown in the country (Fonseca et al., 2012a; Fonseca et al., 2012b; MINAGRI, 2015). Recently, the WF for grape production was estimated using a life cycle assessment approach (Vázquez-Rowe et al., 2017). Studies have concluded that splitting the blue water component into surface and groundwater is important owing to their differences in access, reliability and availability (Rezaei Kalvani et al., 2019); however, none of these studies have distinguished the relative split in irrigation demand between surface and groundwater. Although the volumetric WF indicates the magnitude of water consumption, it does not show potential issues associated with water scarcity and over-exploitation of resources, which depends on local hydro-climatic conditions.

There are several frameworks available in the literature to assess groundwater sustainability that rely on specific indicators to evaluate environmental, socio-economic and institutional dimensions (e.g., Hosseini et al., 2019; Pandey et al., 2011). Due to its economic importance and critical water resource situation, the Ica Valley has been the focus of numerous hydrological and hydrogeological studies, trying to quantify the available water resources and characterise the aquifer and its interconnections with surface water (ANA, 2017; Peña et al., 2010). the most common approach to assess groundwater use sustainability in Ica has been a comparison between water abstraction and aquifer recharge (ANA, 2017; Cárdenas, 2012; Tahal Consulting Engineers, 1969). Aquifer recharge includes direct recharge from the river and leaking distribution channels, and indirect recharge from irrigated land (ANA, 2017), which indicates a need to consider the links between type of farms (e.g., large-scale with irrigation technology, small-scale with traditional irrigation systems), irrigation needs and aquifer recharge potential. Scientific evidence has recommended in water use assessments to accompany the water consumption (i.e., volumetric water footprint) with metrics that reflects the benefits of the water appropriation in combination with local impacts of water consumption, including water scarcity (FAO, 2019).

Water footprints can be analysed in the context of economic water productivity to inform micro-level decision making on crop choice (Hogeboom and Hoekstra, 2017) and assessed under existing water availability conditions. Exemplars of water scarcity indicators have applied withdrawal-to-availability (e.g., Smakhtin et al., 2004; Milà I Canals et al., 2009) and consumption-to-availability ratios (e.g. (Hoekstra et al., 2012; Berger et al., 2014)) with the need to meet environmental flow requirements, while others (Wada and Bierkens, 2014) have emphasised the ratio of consumptive water use from non-renewable groundwater and surface water over-abstraction. Impacts on groundwater sustainability can also be evaluated through the water debt indicator (Tuninetti et al., 2019), which measures the time required to replenish water resources used for annual crop production. Nevertheless, the groundwater debt considers the water renewability exclusively generated by rainfall and without including recharge from irrigated fields and other water inflows, such as water leakages. These are key aspects to consider for groundwater recharge in semi-arid and arid regions (Scanlon et al., 2006). Thus, there remains a lack of multi-criteria assessment to evaluate the trade-offs between irrigation needs and aquifer recharge potential across different crop mixes and farming systems. This paper therefore critically evaluates the impacts of irrigated agricultural expansion on water availability in the Ica Valley and the environmental sustainability implications for the Ica-Villacuri aquifer. This was achieved through two over-arching objectives: (i) to analyse historical trends in cropped area, the composition between small and large-scale farms, and trends in agro-export trade in order to understand the current water-related challenges linked to agricultural expansion, and (ii) to perform a multi-criteria assessment of irrigation water to assess the blue water consumption, related economic benefits and the long-term sustainability of water resources considering current crops composition and farming types across geographical zones in the valley.

2. Materials and methods

In this study we applied a combination of spatial analysis of farm-scale types and irrigation modelling, followed by a multi-criteria assessment on irrigation water use for eight geographical zones within the Ica Valley (Fig. 1). Historical trends in cropped area were analysed using Landsat satellite imagery to identify agricultural expansion and the changing composition between small and

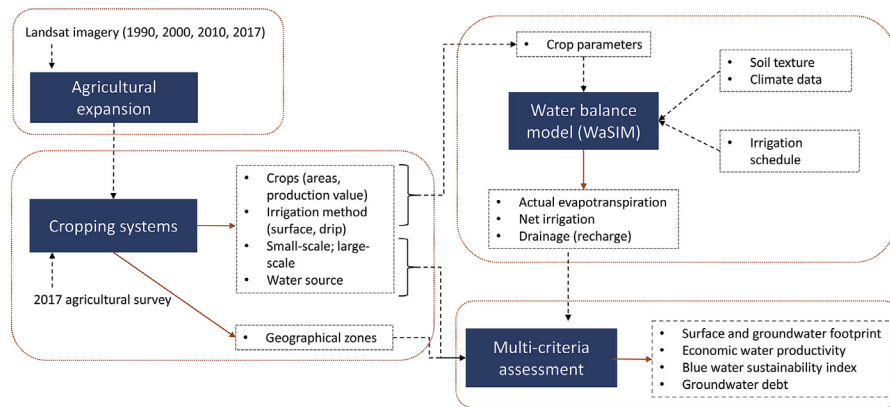


Fig. 1. Schematic diagram of the proposed methodological framework.

large-scale farms. Trends in agro-export trade and agricultural production were calculated using published statistics to understand the current water-related challenges linked to international food markets. We then estimated the blue water footprint from groundwater and surface water sources by farm type for 15 individual crops, and calculated the economic water productivity for each of the geographical zones. Indicators were used to assess the long-term environmental sustainability and renewability of water resources considering the current composition of farming systems across the geographical zones.

2.1. Study area

The Ica Valley is located in Ica province, within the Ica department, south of Lima in central and coastal Peru (Fig. 2). The reported population in the Ica department in 2017 was around

850,000 (INEI, 2018a). Due to work opportunities linked to agricultural expansion, Ica is an attractive area for immigration, resulting in a relatively low poverty index with almost zero unemployment (INEI, 2018b). The Ica Valley can be classified as a hyper-arid zone (FAO, 1989) with a mean annual precipitation of just 10 mm. The climate is typically warm and dry all year around, characteristic of a desert area. The Ica River rises in the Andean mountains of Huancavelica at 4500 m above sea level and flows into the Pacific Ocean with a total basin area of 7188 km². The hydrological regime distinguishes three significant periods, (i) from September to December, surface water comes from the Choclococha system (a network of lakes and channels that transfers water from the Amazon basin), (ii) from January to April, the superficial water comes from upstream rainfall or the melting of the glaciers in the Huancavelica Department, and (iii) for the rest of the year, the Ica River is dry (Oré, 2005).

The Ica-Villacuri aquifer consists of sandy-clayey and sandy-silty porous media, which provides rapid infiltration, and the geology has a high capacity for water retention. The river is the main source of aquifer recharge (Peña et al., 2010); in 2017 recharge was estimated to be 266 Hm³ with over half (54%) and a further third (33%) coming from the Ica River and recharge from irrigated areas, respectively (ANA, 2017). Historically, groundwater, which is available all year, was used to complement surface water and distributed through open channels to the fields. However, there has been a reduction in water resources not only due to over-exploitation of the aquifer, but also due to a reduction in glacial snowmelt (Peña et al., 2010).

2.2. Cropping in the Ica Valley

It has been reported that 94% of soils in the valley are suited for irrigated agriculture (Oré, 2005). Based on agricultural survey data for 2017 (INEI, 2017a), fifteen crop types were selected, which accounted for 92% of the total cropped area (45,180 ha) and 97% of production (1645 million soles total economic value). Asparagus and grapes represented half the area (52%) and 68% the value of production. Six crops were annual including beans, maize, cotton, onion, potatoes and pumpkin; the rest were permanent (asparagus and tree crops such as grapes, jojoba, pomegranate, avocados, pecans, olives and citrus). The 2017 agricultural survey distinguishes between small and large-scale farms. Large farms typically occupy more than 50 ha cropped land and were all surveyed in the 2012 Agricultural Census (INEI, 2012). For small farms (up to 50 ha) a stratified sample was taken with the probability of selection reported. All aggregated figures from the 2017 agricultural survey

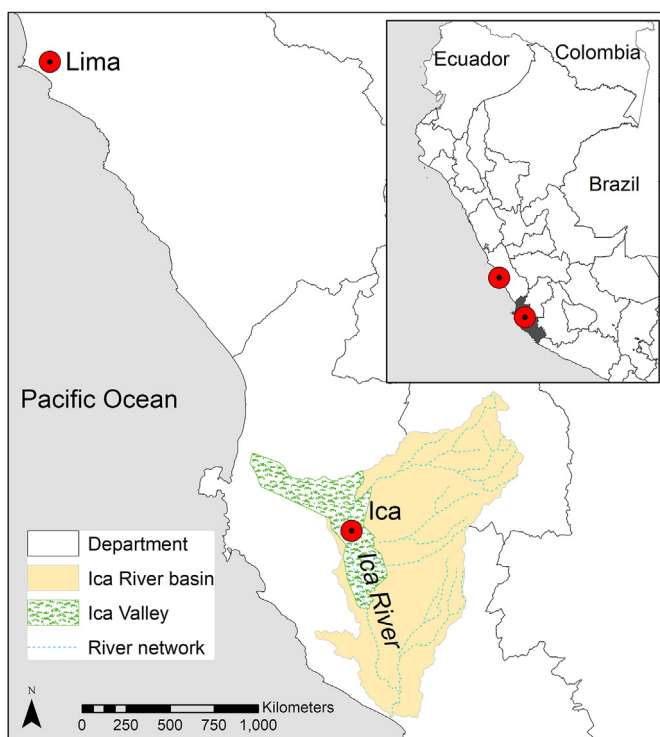


Fig. 2. Location of Ica Valley and Ica River basin in Peru.

were calculated using expansion factors, i.e., weighting values for each observation with the inverse of selection probabilities (INEI, 2017b).

By farm type and for the valley, we studied crops that represented more than 10% of the total cropped area. A summary of reported crop types, split by type of farm, water source and irrigation method is given in Table 1. Asparagus, grapes and avocado are grown by both large and small-scale farmers. For small-scale farms, surface irrigation with surface water is the most widespread irrigation method, except for asparagus; whereas large-scale farms mainly rely on groundwater and drip irrigation. Only grapes and avocados use different water sources and irrigation application methods, depending on farm type.

2.3. Historical analysis of agricultural expansion and farm types

An important component of the study was to understand spatio-temporal trends in agricultural expansion, including changes in irrigated area and the types of farming systems (small and large-scale). To distinguish farm types, we used the georeferenced National Land Cadaster Registry (only available for 2003) which relates all agricultural plots to their owners (farmers) and type of farm production (large-scale, small-scale). As some farmers (or agribusinesses) may have heterogeneous and non-adjacent plots, we combined Landsat imagery with Object Based Image Analysis to generate an automated identification process based on training samples and the Classification and Regression Tree (CART) algorithm as described by Zhang et al. (2018). After obtaining a precise identification of small and large farms for 2003, we then replicated the same algorithm using similar 30m Landsat imagery for 1990, 2000, 2010 and 2017 (Gayoso, 2019). GIS analyses were then used to evaluate agricultural expansion in the valley highlighting where new areas of cultivation have replaced desert and other transitions between small and large-scale farms, and urban and agricultural land. As a check, customs data relating to agricultural export trade (US\$ million) from the Ica Valley for 1994 to 2017 (SUNAT, 2017) were also analysed to identify agro-export companies with water abstraction licences (ANA, 2019a) in the Ica province. The identified rate of expansion was consistent with the agro-export data. Historical analysis of agricultural production for each crop in the Ica Department was based on data for the period 1970 to 2017

(MINAGRI, 2019a).

2.4. Soil water balance modelling

WaSim (Hess et al., 2000) is a daily time-step soil water balance model that has been widely used for international agricultural and hydrological research, including studies relating to the estimation of irrigation requirements (Daccache et al., 2015; Green and Weatherhead, 2014), run-off generation (Hess et al., 2010), potential groundwater recharge (Holman et al., 2009) and water footprinting (Chatterton et al., 2010; Hess, 2010). The WaSim model can work in batch mode which provides flexibility when modelling multiple crop types. In this study the WaSim model was parameterised and used to estimate the annual irrigation needs for 15 crop types. It requires information relating to crop development, soil textural characteristics and daily rainfall and reference evapotranspiration (ET_0) to estimate actual evapotranspiration (ET_a), net irrigation and drainage (recharge). The model was parameterised using data for 2017 for 15 crops assuming a single soil textural class. Reference evapotranspiration (ET_0) was estimated using temperature data from San Camilo station (Lat 14°4'S; Lon 71°42'W, altitude 407 m) and an ET_0 program developed by Hess (2009). For rainfall, monthly averages were used to fill missing values in the time series. Crop cover development data were derived from the literature. For example, planting and harvesting dates were derived from the planting and harvesting calendar from the Peruvian Ministry of Agriculture and Irrigation (MINAGRI, 2019b) and crop development dates obtained by interpolation using FAO (2006).

Irrigation needs for a given crop depend on the timing and frequency of irrigation (schedule). In this study, the irrigation schedule distinguished between surface and drip irrigation application methods. Surface irrigation typically applies larger depths on a less frequent interval, in contrast to drip irrigation which applies smaller, more frequent application depths. For drip irrigation, the schedule was designed to return the soil back to field capacity on a daily basis, for all crops except grapes, olives, pomegranates and jojoba, since they are known for being managed using deficit irrigation practices (Ferreira et al., 2012; Talози and Al Waked, 2016). Grapes were assumed to be deficit irrigated between the veraison (1st October) period until the next bud-break (1st June) assuming the soil water deficit (SWD) was allowed to reach 100 mm and then

Table 1
Crops selected in the Ica Valley by type of farm size (large-scale and small-scale), indicating: the cropped area (ha), water source for irrigation (GW: groundwater; SW: surface water), the percentage of the cropped area irrigated with groundwater source (%GW) and the irrigation method used. Data refer to 2017.

Crop	Large-scale farms				Small-scale farms			
	Area (ha)	Water source	% GW	Irrigation method	Area (ha)	Water source	% GW	Irrigation method
Asparagus	9326		100		2943	GW	95.4	Drip
Grapes	9080		98.5		2136	SW	29.3	Surface
Avocado	1806		100		332		74.8	
Jojoba	2651	GW	100	Drip				
Pomegranate	2130		100					
Olive	1014		100					
Onion	777		100					
Tangelo	646		100					
Tangerine	642		100					
Corn					2825		53.2	
Cotton					1394		16.5	
Potato					1262	SW	32.7	Surface
Pecan					954		55.6	
Bean					835		22.3	
Pumpkin					272		0.0	
Total	28,074				12,953			

Source: INEI (2017b).

irrigated back to a 50 mm SWD. Between veraison and harvest (22nd December) water stress will have a minimal or no effect on yield and excessive irrigation can increase rot and delay fruit maturity (Peacock et al., 1998). After harvest, irrigation was then used to provide at least 20% water requirements by the end of the year as in Ica the amount of rainfall is negligible. In olives the same irrigation deficit plan as for grapes was implemented during the fruit growth between 5th February and 20th April as well as after harvest (1st August); an irrigation strategy that can save water while maintaining good yield of high quality fruit (Goldhamer, 1999). For jojoba we assumed the same irrigation deficit schedule as used for olives and for pomegranate the same as for grapes. For surface irrigation, the schedule was defined with a fixed application to replace mean daily evapotranspiration (4 mm/day: May–August; 5 mm/day: April–September; 6 mm/day: remaining months) in order to avoid crop water stress. Deficit irrigation was assumed for grapes by reducing the irrigation dose after veraison to 4 mm/day. Table 2 summarises the parameter values used in WaSim and their data sources are given in the Supplementary Material (Tables A1, A2).

2.5. Multi-criteria assessment of irrigation water use

For agricultural irrigation, several indicators were required to evaluate water abstraction, its economic benefits and the implications for the sustainability of water resources. This study used four complementary indicators with a distinction between type of water source (surface, groundwater) and farm (large and small-scale). To spatially distinguish the variety of large and small farms the valley was divided into eight geographical zones, based on Landsat imagery data from Gayoso (2019) and the 2017 agricultural survey (INEI, 2017a). As small and large-scale farms tend to cluster together in the valley, the eight zones were defined based on two criteria, (i) location in the valley in terms of the Ica River downstream flow and (ii) predominance of farming systems. This zoning was useful for identifying patterns in water abstraction depending on location and/or predominant type of farming in the Ica Valley. The cropped area (ha), production (t) and economic value (sol) for each crop were projected using the survey's expansion factors (see Section 2.2.) by type of farm and water source and aggregated for each geographical zone using the 2017 agricultural survey (INEI, 2017a).

2.5.1. Surface and groundwater footprints

The water footprint (WF) represents the amount of water consumed by a nation or a specific geographical location, by sector, product or company (Hoekstra et al., 2011). For croplands, the WF distinguishes the blue (WF_{blue}) (i.e. the surface and groundwater evapotranspired by crops) and the green components (WF_{green}) (i.e. the water consumed at the point where rain falls) (Mekonnen and Hoekstra, 2011). In arid and semi-arid environments, where precipitation is scarce and agriculture relies almost entirely on

irrigation, the WF_{green} can represent less than 10% of the consumptive WF (Chukalla et al., 2015). Given the negligible rainfall in the Ica Valley, and as in previous WF research in arid areas (Shtull-Trauring and Bernstein, 2018) its assessment was therefore not considered in this study. The methodology proposed by Hoekstra et al. (2011) was used to estimate the volumetric WF_{blue} (m^3) of croplands in the Ica Valley.

The WF was calculated by crop, by farm type (i.e., small-scale, large-scale), water source (i.e., surface, groundwater) and irrigation method (i.e., surface, drip) for the eight geographically differentiated zones. The distinction between surface and groundwater highlights the water source for the two farming types and supply throughout the year. In the Ica Valley most water used by the large agro-export farms is groundwater, which is available all year round. In contrast, small-scale farmers rely mainly on seasonal surface flows from the Ica River.

For each crop and geographical zone, the WF_{blue} (m^3) eq. (1) was calculated as the accumulated daily evapotranspiration (ET_{blue}) over the length of the growing period in days (l_{gp}) from planting to harvest, multiplied by the crop area per water source (surface, groundwater) and type of farm (small, large-scale).

$$WF_{blue} (m^3) = \sum_{d=1}^{l_{gp}} 10 \times ET_{blue, crop, method} (mm) \times crop\ area_{source, farming\ type} (ha) \quad (1)$$

Cropped areas were obtained from the 2017 national agricultural survey (INEI, 2017a), using an expansion factor to account for sampling probabilities. ET_{blue} (mm) eq. (2) was derived from the WaSim modelling as the difference between the daily actual crop water use (ET_a) and rainfall, when rainfall < ET_a .

$$ET_{blue, crop, method} (mm) = \sum_{d=1}^{l_{gp}} ET_a (mm) - \sum_{d=1}^{l_{gp}} rainfall (mm) \quad (2)$$

The irrigation needs (mm) were also derived from the WaSim modelling and defined as the amount of irrigation scheduled for the crop based on irrigation method (drip, surface). The outputs were compared with other published studies in the literature.

2.5.2. Economic benefits and environmental sustainability in irrigation water demand

To evaluate the economic benefits relating to the WF of crops, we used the concept of water productivity (WP, soles/ m^3) defined as the ratio between crop financial returns (soles/ha) to crop evapotranspiration (m^3 /ha) (Playán and Mateos, 2006). The WP index can support the identification of improvements in the efficiency of the consumptive part of irrigation needs across different crops and farm types. The economic values (sol) and cropland area (ha) were obtained from the 2017 agricultural survey (INEI, 2017a).

Table 2
Input data and parameters required by WaSim.

Data	Parameters	Source
Climate	Rainfall and reference evapotranspiration	San Camilo station (SENAMHI, 2015)
Soil	Drainage coefficient, curve number, water content fractions (saturation, field capacity and permanent wilting point)	Batjes (2005), Hess et al. (2000), USDA (1986; 2009)
Crop	Crop cover development dates: Planting, harvest, emergence, 20% cover, full cover, maturity and maximum root. Roots: Planting depth and maximum root depth. Cover: Maximum cover (%), crop coefficient and mulch cover (%). Transpirations: P-fraction and yield response.	Allen et al. (1998), Bhandana and Lazarovitch (2010), Branch et al. (2014), Doorenbos et al. (1979), FAO (2006), Fonseca et al. (2012a), Lemus (2004)

To assess environmental sustainability, an indicator was used to determine the fraction of the WF_{blue} that was met from non-sustainable water resources. Here, the blue water sustainability index (BIWSI) defined by Wada and Bierkens (2014) was used to provide a single indicator per water source on a monthly time step for reference (2017) year. The BIWSI index represents the proportion of the water consumption that takes place under unsustainable water conditions and ranges from 0 to 1. The $BIWSI_{surface}$ index eq. (3) was calculated dividing the surface water over-abstraction (SW_{oa} , in $m^3/month$) by the WF from surface water ($WF_{blue, surface}$, $m^3/month$):

$$BIWSI_{surface} = \frac{SW_{oa}}{WF_{blue, surface}} \quad (3)$$

Surface water over-abstraction (SW_{oa}) eq. (4) reflects the amount of environmental flow requirements (EFR) that are not satisfied due to local surface water consumption:

$$SW_{oa} = \begin{cases} 0, & WF_{blue, surface} < SWA \\ \max(0, & WF_{blue, surface} - SWA) \end{cases} \quad (4)$$

Surface water availability (SWA, $m^3/month$) was approximated with the monthly flow in the Ica River including water transfers from the Choclococha system (ANA, 2017) minus the EFR, which were defined as Q90 (i.e. the monthly streamflow that is exceeded 90% of the time), following Smakhtin et al. (2004). Naturalised monthly average river flow data was obtained from Canales Torres (2015). The $BIWSI_{surface}$ provides a single indicator for the whole valley.

$BIWSI_{groundwater}$ eq. (5) was then calculated as the ratio between non-renewable groundwater abstraction ($NRWG_a$, $m^3/month$) and the WF from groundwater ($WF_{blue, groundwater}$, $m^3/month$) for each of the eight defined geographical zones within the Ica Valley:

$$BIWSI_{groundwater} = \frac{NRWG_a}{WF_{blue, groundwater}} \quad (5)$$

$NRWG_a$ was calculated as the difference between $WF_{blue, groundwater}$ and groundwater recharge ($m^3/month$). Average monthly groundwater recharge was obtained from ANA (2017), which included the recharge from the Ica River and tributaries, water channels and irrigation water return flows. The sum of the recharge from the river, tributaries and water channels was then divided by the whole Ica-Villacuri aquifer area (127,440 ha) to derive an annual water recharge per unit area (i.e., 142 mm). The estimated recharge per unit area in the aquifer was later multiplied by the area of the aquifer within each zone in order to estimate volumetric recharge.

The monthly recharge from irrigation as reported in ANA (2017) was replaced by our calculated drainage recharge after applying an efficiency factor to account for surface irrigation management (scheduling) and then divided by the total cropped area in each of the eight geographical zones. With surface irrigation only a percentage of the water applied is consumed by the crops and hence can be considered as the water efficiency of the irrigation schedule. It was estimated by dividing the actual evapotranspiration (ET_a) by the irrigation depth obtained from the WaSim modelling. We assumed an application efficiency of 60% (Phocaides, 2007; Iberico, 2012), which also implicitly considered water losses in the irrigation schedule. It was assumed that the drainage recharge increased proportionally to the gross irrigation application. An efficiency factor was not considered for drip irrigation as the WaSim model assumed that under an optimal irrigation schedule the recharge under drip irrigation was zero.

Finally, the sustainability of water use to support irrigated agriculture was also assessed by using the 'water debt repayment time' indicator developed by Tuninetti et al. (2019) to be adapted to groundwater sources in desert areas. The water debt ($WD_{groundwater}$) provides a physical quantification of the time required to replenish a groundwater resource consumed for crop production. The $WD_{groundwater}$ (year) eq. (6) index was therefore calculated for each of the eight geographical units by dividing the annual $WF_{blue, groundwater}$ ($m^3/year$) by the water renewability (WR , $m^3/year$) defined as the total groundwater recharge.

$$WD_{groundwater}(year) = \frac{WF_{blue, groundwater}}{WR_{river} + WR_{channels} + WR_{irrigation}} \quad (6)$$

It was assumed that water recharge generated locally in the Ica-Villacuri aquifer represents an amalgamation of recharge from the Ica River and its tributaries (WR_{river}), the water channels ($WR_{channels}$) and irrigation water return flows ($WR_{irrigation}$). This is in contrast to Tuninetti et al. (2019) whose method only included recharge from rainfall, which is negligible in desert areas. The WR_{river} , $WR_{channels}$ and $WR_{irrigation}$ indices were calculated using a similar approach to that for groundwater recharge in $BIWSI_{groundwater}$.

Using 'year' as a metric in the $WD_{groundwater}$ indicator helps to provide a better understanding of how long it takes for the hydrological cycle to renew water consumed for irrigation in the Ica Valley. When the numerator is lower or equal to the denominator, then the resource is considered to be used sustainably. In contrast, if the numerator is higher than the denominator, this implies that water resources are being used faster than the rate of renewal, and therefore, agricultural production is locally unsustainable and will lead to a depletion of groundwater resources.

3. Results and discussion

In this section the main results relating to agricultural expansion in the valley and its effects on the sustainability of water resources are presented and discussed. Historical changes in agricultural areas by farm type are provided, while the volumetric blue water footprint for 2017 across the valley is presented considering the cropping patterns per geographical zone and water sources used. A set of indicators were derived to highlight the economic benefits linked to irrigation in the valley and the unsustainable levels of water consumption due to depletion of non-renewable groundwater resources. The importance of differentiating large-scale and small-scale farming for the assessment of groundwater recharge is also discussed. The Ica Valley is an example of depleted resources virtually embedded in food exports and recommendations for adaption management strategies are provided in support of more sustainable management of water resources in the region.

3.1. Historical changes in agricultural and agro-export expansion

Based on our temporal analysis, the irrigated area in the Ica Valley increased from 34,260 ha to 55,175 ha between 1990 and 2017. The area attributed to small-scale farming slightly decreased over this period from 26,440 to 24,455 ha, in contrast to large-scale farming which increased fourfold from 7820 to 30,720 ha over the same period. In other words, in 1990 the area of small-scale farms was 3.4 times the area of large-scale farms, whereas by 2017 large-scale farms have expanded to the extent that they now represent 1.3 times the area of small-scale farms (Fig. 3). There has been a clear and direct relationship between agro-export expansion and the sharp rise in irrigated area and agricultural productivity.

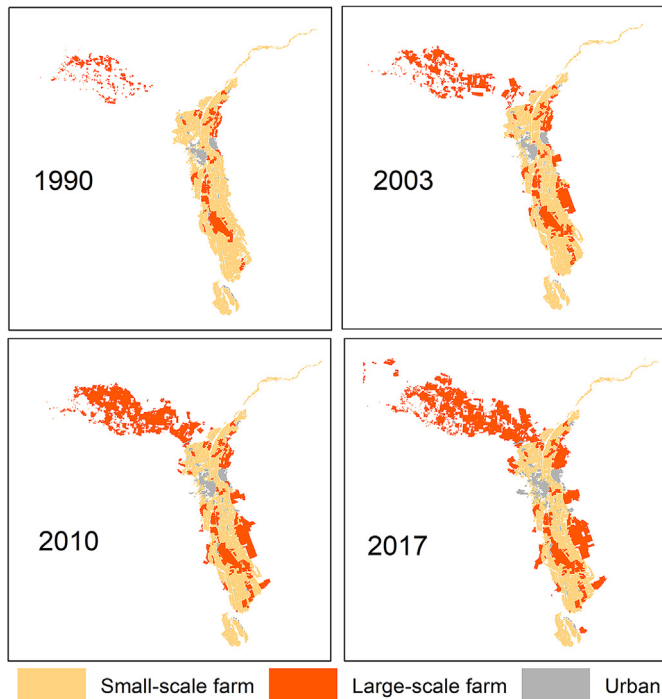


Fig. 3. Spatial distribution of small and large-scale farms for four years (1990, 2003, 2010 and 2017) based on Gayoso (2019).

Agricultural expansion and transformation has specifically come from the agro-export sector with 26 of the 50 main agro-exporting Peruvian companies now established in the area (Rendón-Schneir, 2009). The agricultural frontier has expanded in recent decades due to investments in irrigation infrastructure with increased levels of modernisation in large-scale farms and pumping for groundwater abstraction (Oré, 2005).

Appropriation of water resources has been characterised by an increase in water abstraction driven by the promotion of high-value crops with a constant irrigation supply from groundwater along with the implementation of high efficiency drip irrigation technologies. This agricultural expansion has led to an increase in groundwater abstraction rates due to large-scale farms being located far from the Ica River and thus having to rely entirely on groundwater. Our study showed that nearly three-quarters (72%) of this expansion in large-farms has taken place on land that was previously desert areas, with only 6% being on former small farms. In 2017, most of the small-scale farms were located in the central and south areas of the Ica Valley, whereas a concentration of expansion of large-scale farms has now taken place in the north-west overlying the Villacuri aquifer (Fig. 3). Consequently, agriculture is no longer limited to areas next to the river, but now occupies more arid zones which were previously undeveloped (Damonte and Boelens, 2019).

Total production for the 15 irrigated crops in the Ica Department has remained broadly constant from the 1970s to the 1990s; however, after 1995 the cropped area expanded exponentially (Fig. 4, middle panel). Almost all crops have increased in production, notably asparagus, grapes, maize and onion. The only crop which has shown a decline is cotton, down from 70,000 to 15,000 t between 1995 and 2017, respectively. The agro-export trade (Fig. 4, lower panel) follows a similar pattern to agricultural production and land expansion by large farms, with export trade growing exponentially since 1995.

Socio-political circumstances contributed to the cyclical peaks

and troughs observed in the historical trends in crop production. The Ica Valley was one of the largest producers of cotton in Peru in the 1970s (Rendón-Schneir, 2009) due to new irrigation infrastructure including the Choclococha Project in 1959, agricultural modernisation and supporting national legislation. During the 1970s and 1980s, agricultural expansion slowed as a consequence of the Agrarian Reform which triggered a breakdown in relationships between the government and large-scale farmers (Philip, 2013). Since the 1990s, there has been a period of uninterrupted growth in traditional commodities (De-Silva, 2011), including cotton, and non-traditional products, such as asparagus, grapes, avocados and citrus. Expansion of high-value crops in the Ica Valley has been driven by globalisation and free-trade agreements which have opened international markets (Rendón-Schneir, 2009). This is largely in response to neoliberal reforms which fostered the formation of export-oriented companies boosting the export trade from Andean regions which has also attracted substantial external financial investment. Both agro-exports and the resulting growth in population linked to agricultural employment (Wahlin, 2018), have been associated with trends in concentration of both land ownership and water access (Burneo, 2011; Damonte and Boelens, 2019), and have added pressure on access to water resources for Ica city (Zeisser and Gilvono, 2016).

3.2. WaSim modelled irrigation needs

The irrigation needs (mm) per crop and type of irrigation method from the WaSim modelling can be compared with studies in the area and/or from regions with similar agroclimatic conditions. For instance, the irrigation needs for asparagus in Ica Valley were estimated to be 1509 mm (Fonseca et al., 2012a) which are consistent with our estimation (1523 mm). Studies in other areas with a similar climate such as in Egypt have estimated an irrigation needs of between 780 and 830 mm for maize under surface irrigation (Abd El-Halim and Abd El-Razek, 2014); in the Ica Valley we estimated the equivalent need to be 810 mm. Studies for cotton in arid regions estimated a maximum irrigation need of 910 mm (Ibrahim and Yacoub, 2009) while WaSim estimated 1144 mm (and blue evapotranspiration of 990 mm). In some cases, such as for avocado, the irrigation needs in the comparative study were probably estimated for a region with higher annual rainfall (Steduto et al., 2012) which would in part explain the higher values obtained in WaSim. However, the gross irrigation needs in our study would be slightly higher if water losses and system efficiency were considered. These losses have only been accounted for when calculating potential groundwater recharge, as the water use in this study focuses on the consumptive part of irrigation (i.e., blue water evapotranspiration). The blue evapotranspiration (mm) and irrigation needs (mm) by crop and type of irrigation method are given in the Supplementary Material (Table A3). A comparison between WaSim irrigation need outputs and the published literature for all crops in the Ica Valley is given in Johnson (2019).

3.3. Blue water footprint in the Ica Valley

The WF_{blue} in the Ica Valley in 2017 was estimated to be 483 Mm^3 , with 87% being attributed to groundwater and 13% from surface water. Large-scales farms comprise 81% of the groundwater footprint, whereas small-scale farms account for 97% in WF_{blue} from surface water. Taking into account both water sources, asparagus (187 Mm^3) and grapes (138 Mm^3) have the highest WF_{blue} values followed by avocado (28 Mm^3), jojoba (26 Mm^3), pomegranate (20 Mm^3) and maize (20 Mm^3) (Fig. 5; See Supplementary Material for details of all crops under study). All these crops are intended for agro-export with the exception of maize.

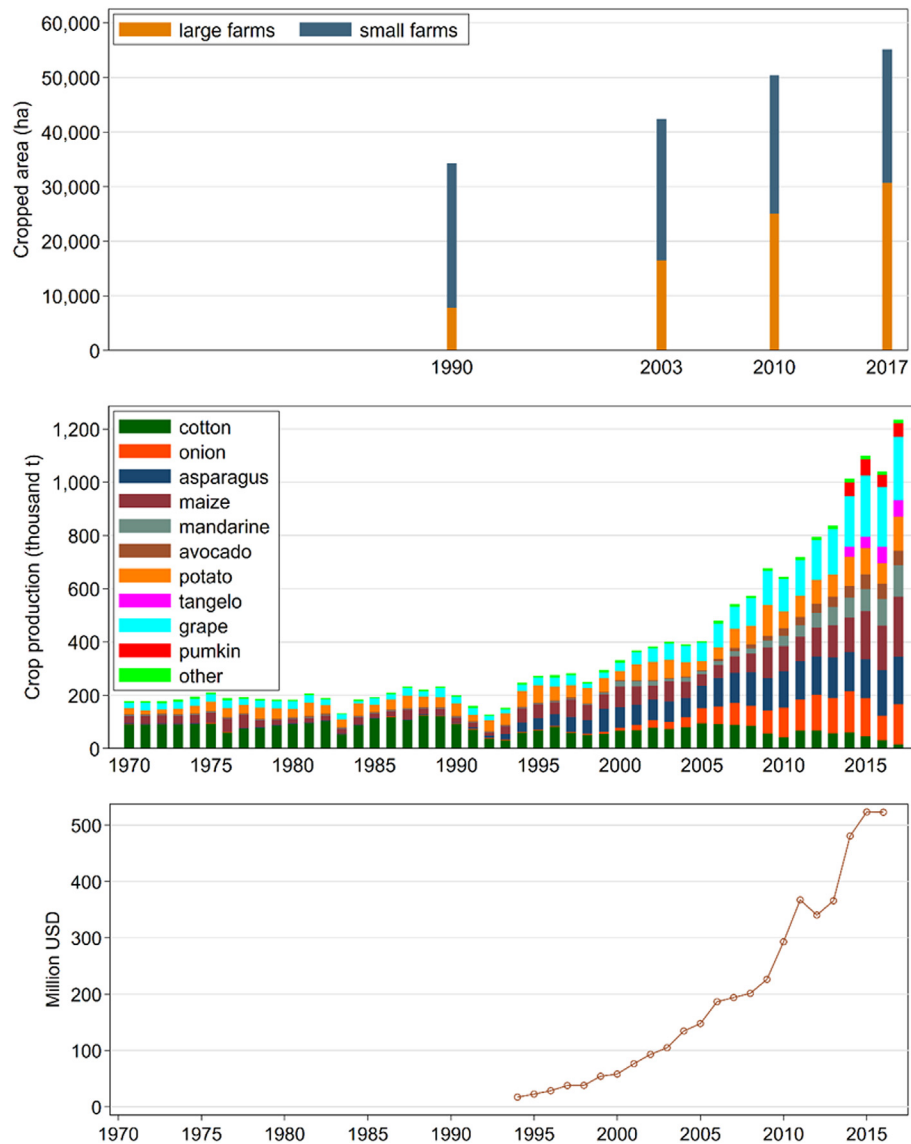


Fig. 4. Historical trends in agricultural area in the Ica Valley (ha) (top panel), crop production in the Ica department (thousands tons) for selected crops (middle panel), and total agro-export trade from the Ica Valley (US\$ million) (lower panel). For crop production, there was no data for pomegranate; tangelo and pumpkin production for the period 2014–2017. Data sources: ANA (2019a), Gayoso (2019), MINAGRI (2019a), SUNAT (2017).

By considering how the WF_{blue} was being allocated throughout the valley we can identify hotspots of water consumption by type of water source. In the high part of the valley, the geographical zone '1. Villacuri: large-scale' is characterised by its complete reliance on groundwater (Fig. 6b). This area constitutes 41% of the total WF_{blue} from groundwater in the valley. The crops that dominate this WF_{blue} include asparagus (31%), grapes (31%), jojoba (16%) and pomegranate (11%). Grapes, avocado, maize and pecan are found in the small-scale farming zone from the upper part ('2. High valley: small-scale') (Fig. 6c). In the low part of the valley, the zone with the second largest WF_{blue} was identified ('8. Low valley: large-scale'), where 95% of the WF_{blue} was abstracted from groundwater. Irrigation consumption here is dominated by asparagus (86%), followed by grapes (10%). In the middle part of the valley cotton is mostly grown by small-scale farms ('5. Middle valley: small scale'). The Supplementary Material summarises the estimated WF_{blue}

volumes by geographical zone, and by crop type and water source (Table A4).

3.4. Water productivity, blue water sustainability index and groundwater debt

In 2017 water productivity ranged between 0.7 sol/m^3 (in '4. Peri-urban small-scale' depending only on surface water source) to 5.4 sol/m^3 (in '3. High valley: large-scale') (Fig. 7a). Some areas showed higher productivity than others given their crop mix, with large-scale farms having higher water productivity, leading to different water productivities linked to the types of water sources used. For example, in '3. High valley: large-scale' over three-quarters (81%) of the WF_{blue} was from groundwater (Fig. 7b). Here grapes and tangerine generate 6 and 13.2 sol/m^3 water productivity, respectively (see Table A5 in Supplementary Material). In

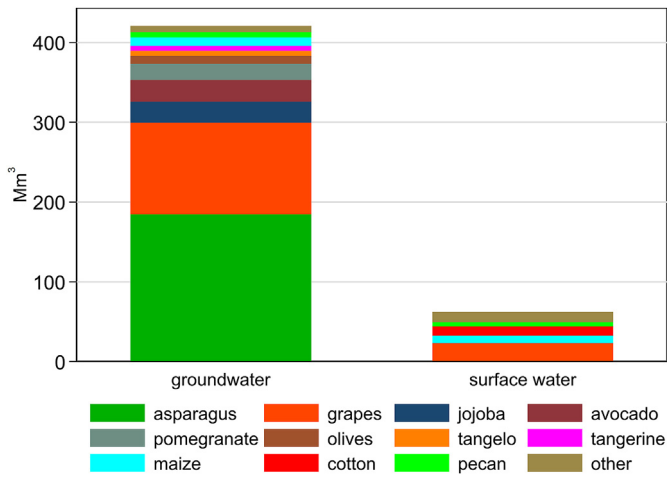


Fig. 5. Allocation of WF_{blue} (Mm^3) by crop for the year 2017, distinguishing between surface and groundwater sources for the Ica Valley.

'2. High valley: small-scale' a 4.2 sol/m^3 water productivity was estimated, which is largely due to grape production (7.1 sol/m^3). The lower values of water productivity in '4. Peri-urban small-scale' and '5. Middle valley: small-scale' can be attributed to the allocation of about 30–50% of the WF_{blue} to cotton, which has a water productivity below 0.6 sol/m^3 .

The blue water sustainability index (BIWSI) was calculated on a monthly time-step for both surface and groundwater. About $6 Mm^3$ surface water use was estimated to be unsustainable between May to August. Unsustainable water use peaked in June and July with a value in excess above 40% of the $WF_{blue, surface}$ (representing both months $3.8 Mm^3$) (Fig. 7b). Unsustainable water use was assumed to occur at the expense of the environmental flow requirements. Nevertheless, the environmental flow requirements between May and August were zero as the Ica River is dry during this period. This indicates that some farmers who traditionally used surface water will likely shift to abstracting groundwater to compensate for the lack of surface water. From a water management perspective, exploiting the temporal variability of surface water to increase water availability could reduce the pressure on water resources. The water surplus could be stored and used for irrigation during the dry period or the large-scale farms could use it instead of groundwater during the wet period. For instance, the local

organization of groundwater users of Ica (JUSVI - Junta de Usuarios de Agua Subterranea del Valle de Ica), which mainly includes large-scale farms, has an agreement with two small farmers water organizations to use part of the surplus water during the wet season to recharge the aquifer (Damonte and Boelens, 2019).

For groundwater abstractions, $286 Mm^3$ are consumed annually under unsustainable conditions (i.e., exceeding groundwater recharge) with the most unsustainable use occurring in areas of the valley where large-scale farms dominate. The '1. Villacuri: large-scale', '6. Middle valley: large scale' and '8. Low valley: large-scale' showed that after April more than 70% of the volume from groundwater abstractions exceeded groundwater recharge (Fig. 7b). The water debt repayment time for groundwater suggests that 5.7, 4.1 and 3 years are required to replenish water used locally in '6. Middle valley: large-scale', '8. Low valley: large-scale' and '1. Villacuri: large-scale', respectively (Fig. 7c). In most areas, water for irrigation is being used in an unsustainable manner with the exception of '4. Peri-urban: small-scale' and '5. Middle valley: small-scale'. Our study provides valuable evidence of the urgent need to address over-abstraction of groundwater as current levels of water consumption (2017) are much higher than local rates of water renewal. Our water debt repayment times can be compared with the groundwater debt found in water-stressed areas such as the High Plains (7.2 years) and California Central Valley (2–9 years) in the US (Tuninetti et al., 2019).

3.5. Large-scale versus small-scale farming: implications for groundwater recharge

In high-intensive irrigated areas, as the Ica Valley, considering the water renewability as exclusively generated by rainfall and without including recharge from irrigation fields would underestimate water renewability potential. According to our analysis about 10% of the annual groundwater renewability in the Ica Valley comes from the recharge of crops irrigated via surface water application method (i.e., $15 Mm^3$, Table A6 in Supplementary Material), as there is no recharge from drip irrigation. The largest recharge from irrigated areas takes place in the small-scale farm zones from the higher, middle and lower valley with values of 5.9, 3.7, and $3.8 Mm^3$, respectively. The recharge from irrigated areas in that zones represent about 32%, 29% and 32% of their total aquifer recharge in the higher, lower and middle valley, respectively (Fig. 7d; Supplementary Material). This confirms that the current approach for irrigation abstraction to support agricultural expansion is unsustainable, having a much greater impact in geographical

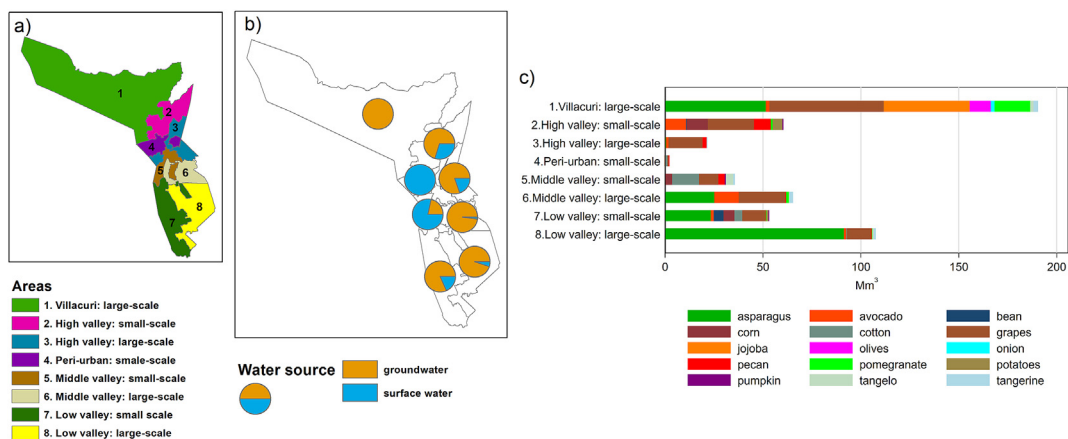


Fig. 6. a) Location of the eight geographical zones the valley was divided into; b) ratio for groundwater and surface water source for each zone in 2017, c) allocation of WF_{blue} (Mm^3) in 2017 by crop and zone.

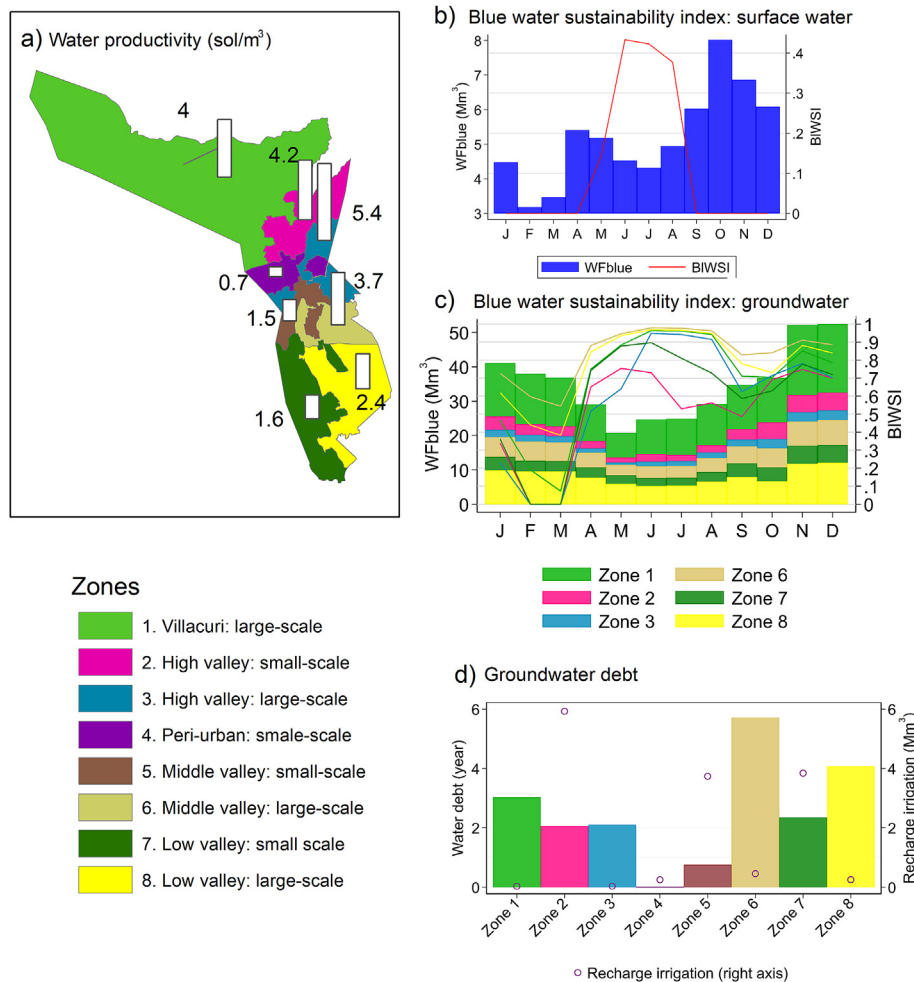


Fig. 7. a) Water productivity, b) blue water sustainability index for surface and c) groundwater, and d) groundwater water debt per zone in the Ica Valley. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

zones where large farms dominate and are dependent on groundwater.

In the valley there is a clear difference in the level of modernisation between agro-export farms, which typically use automated high-efficiency drip irrigation systems, and small-scale farms that rely on low energy, lower efficiency surface irrigation systems (Johnson, 2019). Large-scale farms have access to irrigation water all year and therefore achieve much higher levels of productivity. In contrast, small-scale farmers abstract water from the Ica River as they lack access to finance to drill either new boreholes or to increase their depths to counteract the falling water table (Wahlin, 2018). It has been shown that an increase in yield through precision irrigation, such as the adoption of drip irrigation, can help reduce the WF (Chukalla et al., 2015). However, despite drip irrigation being potentially more efficient in terms of application efficiency and resulting in higher yields and better crop quality, the implications for aquifer recharge due to a reduction in deep drainage that is common with surface irrigation (Jiménez-Martínez et al., 2009; Kendy et al., 2004) has been widely reported (Jiménez-Martínez et al., 2009; Kendy et al., 2004; Rodríguez-Díaz et al., 2011). This is key for the Ica Valley, where recharge from irrigation has taken place due to the widespread use of traditional (surface) irrigation, whereas recharge from drip irrigated systems is negligible.

3.6. Role of Ica Valley in international food trade

Analysing the WF of crop production for a defined area can help identify 'hotspots' of water consumption, and quantify the embedded water in global food trade (Hoekstra et al., 2011). In the Ica Valley the groundwater footprint (421 Mm³) is mainly attributable to large-scale farming enterprises whose primary target destination is the global export market. The two main crops grown for export are asparagus and grapes, which together account for 67% of the total Wf_{blue}, with 92% of the volume abstracted from groundwater. Water resources have been recognized to be virtually embedded and appropriated through the transnational trade of agricultural commodities (Allan, 1997) in a globalised food system with hidden virtual water fluxes (D'Odorico et al., 2019). Food exporting areas are often water-stressed, and therefore, water and food securities are at risk, both locally and globally (Dalin et al., 2017; Wada et al., 2012). The Ica Valley represents a water-stressed exporting region which is spatially disconnected from its consumption source, as shown through global food trade studies (e.g., Dalin et al., 2012; Hoekstra and Chapagain, 2008; Odorico et al., 2014, 2019). The largest proportion of water used for fruit and vegetable production in the Ica-Villacuri aquifer is consumed abroad, including the US, Spain, the Netherlands and the UK (MINAGRI, 2019a).

Virtual water trade means some importing countries rely extensively on water-intensive commodities from elsewhere (Hoekstra and Mekonnen, 2016), but concerns about the long-term sustainability of this practice has been questioned (Suweis et al., 2013) due to growing water scarcity from producing regions (Porkka et al., 2016). Globally, groundwater constitutes an 11% share of depleted resources virtually embedded in food exports (Dalin et al., 2017), which indicates the need to locally assess the environmental implications of virtual water trade given the unsustainable use of water resources (D'Odonico et al., 2019). The findings from this study reinforce this critically important issue of how blue water is embedded in agro-exports in a desert region that is highly dependent on groundwater. If agricultural expansion continues at the same rate as in recent decades, then local water scarcity and unsustainable conditions could generate supply chain risks and affect food trade relationships (Hess and Sutcliffe, 2018). A failure in agricultural production in the Ica Valley would have serious food supply repercussions well beyond Peru.

3.7. Implications of groundwater resources depletion for agricultural production

The Ica aquifer comprises a total of 1861 hm³ of storage capacity with 45% of this volume dependent on regular to good hydrologic conditions (ANA, 2017). Assuming an annual depletion of 286 hm³ and levels of recharge estimated in this study, the aquifer would show unsuitable hydrological conditions within 3.8 years. However, this is something that does not take place in the aquifer uniformly and spatio-temporally given the different hydrological conditions and existing groundwater levels (ANA, 2017). The total groundwater storage and rates of recharge are often not the primary determinants of the rate of storage recovery; in many cases the hydraulic properties and boundary conditions of the aquifer are more important controls (Gleeson et al., 2020).

Aquifers become depleted to a point where further water withdrawal is unviable, either due to environmental limits being reached or excessive extraction costs (Turner et al., 2019a, 2019b). A peak of non-renewable water use is observable where withdrawal rates substantially exceed natural recharge due to over-pumping and/or because groundwater aquifers become contaminated with pollutants that make water unusable (Gleick and Palaniappan, 2010). Over-exploitation of the aquifer in the Ica Valley between 2000 and 2017 has already caused groundwater salinization in certain areas and a decrease in water levels across almost the entire aquifer (ANA, 2017), with a reduction of the water table between wells from 0.31 to 1.84 m/year (ANA, 2018). According to the National Water Authority, if the current rate of decline in the water table continues, within 10 years there could be a 76% reduction in the total area irrigated in the valley due to water scarcity, with increased production costs due to higher pumping costs (ANA, 2018). This situation will put agricultural activities in the valley under serious risk. As shown in previous studies, the economic impacts of a decline in irrigated agriculture in the valley will be particularly acute as in other dry regions (e.g., Middle East) given the limited scope for expanding rain-fed cropland (Turner et al., 2019a). The economic viability of pumping will also be threatened given the increased costs to abstract water. Economic feasibility assessments will be needed to evaluate alternate water sources (e.g. desalination of groundwater) (Aparicio et al., 2019), but given the diversity of farming systems in the valley such initiatives would not be economically feasible for most farmers, particularly for those engaged in small-scale production.

3.8. Promoting adaptive groundwater management strategies

Despite the key role of groundwater in water supply provision, economic development, food security and human well-being, its management has received less attention than more visible surface sources (Famiglietti, 2014). In the Ica Valley, if the capacity for locally renewable water resources increased, then the groundwater debt repayment period could be reduced. This could be accomplished for example by creating areas for artificial groundwater recharge (Satheeshkumar and Venkateswaran, 2020). Instead of decreasing groundwater abstractions, current research in Ica is investigating how to increase recharge using surplus surface water during the wet period (Escolero-Fuentes, 2017). From a demand side, the implementation of taxes to large water users would also support more responsible use and control groundwater abstractions. Taxes for example could be reviewed annually depending on groundwater levels (Graveline, 2019) as a way to incentivise groundwater monitoring. Recently, the national water authority (ANA) implemented a new monitoring system for groundwater users in the Ica-Villacuri area, with support from the World Bank through a project for the integrated management of water resources program (ANA, 2019b). This will likely increase the possibility of implementing such a water tax. However, groundwater is inherently difficult to monitor and regulate, and where legislation exists, it faces major enforcement disputes (FAO, 2017). In the Ica Valley, the ANA faces a major challenge in imposing this tax in a context of powerful opposition from large farmers (Zegarra, 2018), and due to weak governance, poor enforcement, and increased market incentives (Muñoz and Zúñiga, 2018).

Other initiatives to improve agricultural water management could also play an important role in promoting circular economic activities such as the reuse of treated effluent for irrigation, an initiative being promoted by ANA (2013). There are also a few examples of agro-export companies treating and reusing wastewater from domestic uses, although institutional barriers need to be overcome (Monteza et al., 2012) to force agro-export and water utility companies to formalise their water reuse agreement. Moreover, extremely high quality treated wastewater will be needed to avoid soil salinization (Tal, 2016). Agro-export companies use of treated wastewater to irrigate might be constrained in their ability to trade products on the international market due to the need to meet specific quality assurance standards linked to microbiological water quality, particularly for crops that are eaten raw and not processed (Water Technology, 2018).

4. Conclusions and future prospects

This study evaluated the water resource impacts of agricultural expansion to support agro-exports over the last few decades in the Ica Valley and the environmental sustainability implications for groundwater resources. Since the 1990s, cropped areas, production, exports and water abstractions have all increased as a consequence of the socio-political circumstances. Nearly three-quarters of the agricultural expansion involving large-farms (from 7820 ha in 1990 to 30,720 ha in 2017) has taken place on desert areas, indicating that this groundwater-dependent agriculture has expanded in previously undeveloped arid zones. Groundwater resources appropriation has been driven by the promotion of high-value crops for agro-export purposes with a constant irrigation supply along with the implementation of high efficiency drip irrigation technologies.

In 2017, the groundwater footprint represented nearly 90% of total water consumption which was mainly embedded within commodities destined for export. The largest economic water productivities (5.4 sol/m³) were found in geographical zones where

large-scale farming dominates due to existing crop-mix, leading also to larger water productivity from groundwater sources. However, farming systems influence differently on groundwater renewability and the opportunities to mitigate unsustainable groundwater abstractions. Recharge from drip irrigated systems in large-scale farming is negligible, whereas about 10% of the annual groundwater renewability in the Ica Valley comes from the recharge of small-farming irrigation via surface water application method.

The existing agro-export model in the Ica Valley could be under risk due to declining water levels and increased pumping costs. In 2017, 286 Mm³ of groundwater abstraction were consumed under unsustainable conditions (i.e., exceeding groundwater recharge). Cropland production is locally unsustainable and dependent on water resources created upstream, with the largest impact in areas of the valley with the concentration of large-scale farms, where between 2.1 and 5.7 years are required to replenish water resources consumed in 1 year. The support to irrigated agro-export crops has led to an unsustainable use of water resources and threatens the long-term sustainability of groundwater resources in the region. There is thus a need to improve water resources management by increasing water availability and water renewability if the current model for agricultural production and expansion is to continue. Otherwise, urban water supplies, agricultural economic activities, and the countries which rely extensively on imports of fruits and vegetables from Peru will be negatively affected.

Future research will need to consider how recharge is spatially distributed in the Ica Valley, such as studies undertaken in the US High Plains and Central Valley (Scanlon et al., 2012), to overcome the limitations of assuming a constant aquifer recharge. More detailed assessment and measurement of the recharge capacity linked to surface irrigation (source and application method) from small farmers will also be an important research gap to address, as well as an economic valuation of the related environmental benefits, currently not recognized by water authorities. A partial recovery of the aquifer in the Ica Valley could also be supported by additional artificial water recharge from winter river flows. The increased costs associated with deeper wells will need to be estimated within the context of both existing and future socio-economic inequalities in order to assess the long-term economic feasibility of crop production. This type of studies will provide much needed evidence to support policy makers in promoting the long-term sustainability of groundwater resources and agricultural expansion. Collaboration between researchers and the national water authority will be key to maximising the benefits for decision-making by applying state of the art knowledge in groundwater modelling to help identify options for irrigated agricultural systems that are resilient to future water scarcity.

CRediT authorship contribution statement

Gloria Salmoral: Conceptualization, Methodology, Formal analysis, Writing - original draft. **Araceli Viñarta Carbó:** Conceptualization, Methodology. **Eduardo Zegarra:** Conceptualization, Writing - review & editing. **Jerry W. Knox:** Conceptualization, Supervision, Writing - review & editing. **Dolores Rey:** Conceptualization, Supervision, Writing - review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.jclepro.2020.123544>.

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